Microwave Rectification at the Boundary between Two-Dimensional Electron Systems.

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Rectification of microwave radiation (20-40 GHz) by a line boundary between two two-dimensional metals on a silicon surface was observed and investigated at different temperatures, in-plane magnetic fields and microwave powers. The rectified voltage V_{dc} is generated whenever the electron densities $n_{1,2}$ of the two metals are different, changing polarity at $n_1 \approx n_2$. Very strong nonlinear response is found when one of the two 2D metals is close to the electron density corresponding to the reported magnetic instability in this system.

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I. INTRODUCTION

Dilute low dimensional systems have been the focus of a great deal of recent attention due to their interesting physical properties at low temperature [1]. A number of fascinating phenomena have been reported for low-density electron systems in high mobility silicon inversion layers as a function of magnetic field. A dramatic increase of the resistivity in response to in-plane magnetic field has been shown to be associated at high electron density with complete spin polarization of the carriers [2–4]. A number of experiments have recently shown that the spin susceptibility increases substantially as the density is decreased [2,5,6], indicating a possible divergence and ferromagnetic instability at finite electron density. Through a detailed study of the magnetoconductivity as a function of temperature and electron density, we have identified an energy scale Δ associated with the response of the electrons to a magnetic field applied parallel to the plane of the electrons [7]. The density-dependent energy Δ was found to go to zero at a finite density n_0, signaling critical behavior and the occurence of a zero-temperature quantum phase transition of magnetic origin.

Microwave radiation may be an interesting tool for probing the behavior of these systems. At low frequencies $\hbar\omega \ll \Delta$ the system is expected to behave as a correlated spin liquid, while at high frequencies $\hbar\omega \gg \Delta$ the behavior will be similar to that of an noninteracting gas. In response to microwave radiation of frequency ω, one may find particularly interesting behavior at the boundary between two metallic regions which have characteristic energies Δ_1 and Δ_2 if $\Delta_1 < \hbar\omega < \Delta_2$, corresponding to transport between a correlated spin liquid and a noninteracting gas.

In this paper we report unusual high frequency behavior of dilute 2D electron systems in multigated high mobility Si-MOSFET's. We investigated the nonlinear microwave response of the boundary between two regions of the silicon inversion layers with different electron densities. A rectified signal is observed whenever the electron densities $n_{1,2}$ of the two metals are different. The polarity of the rectified signal can be changed easily by varying the electron density on the two sides of the boundary. We find that the nonlinear response of the boundary between the two metals is unusually strong when one of the metals is close to the quantum phase transition reported earlier [7] while the other is kept at high electron density - a condition which corresponds to $\Delta_1 < \hbar\omega < \Delta_2$.

II. EXPERIMENTAL SETUP

We used multigated Si-MOSFET's with six different contacts, shown schematically in Fig. 1. The 2D electron densities n_i corresponding to different contacts were separately controlled by independent gates (contact gates). Each 2D metal system was adjacent to a common 2D conducting region of density n_2, also controlled independently by a main gate. The region between the main gate and each contact gate was in the form of a thin-line split. The narrow split between gate metallizations was obtained by reactive ion etching [8]. The typical width of a split ($50-70$ nm) was less than the thickness of the Si oxide insulating layer (152 nm), providing a smooth, probably monotonic, profile of electron density between two 2D layers with different gate voltages, as shown in Fig. 1 (c). The orientation of two splits, shown as vertical lines on the surface of the structure in Fig. 1(a), was perpendicular to the orientation of the remaining four horizontal splits. The two contacts corresponding to the vertical splits were permanently connected to ground.

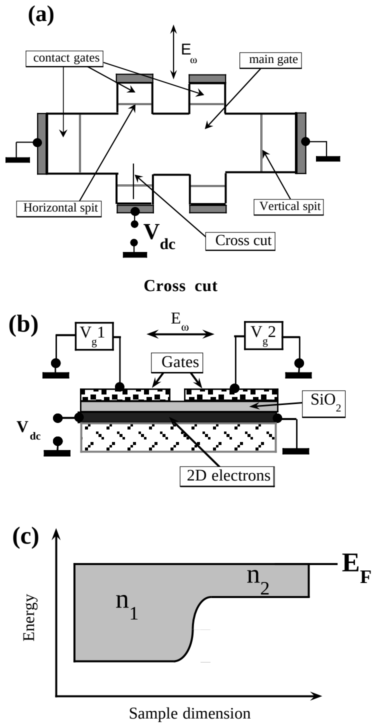


FIG. 1. (a) Top view of the sample. (b) Cross-sectional view of the sample between one contact area and the main sample area. The regions under the two gates form two different 2D metals (2D-Metal #1 and 2D-Metal #2). (c) the Fermi level and bottom of the conduction band are shown as a function of position along the sample. The shaded area below the Fermi level corresponds to occupied electron states of the two 2D metals with different electron densities n_1 and n_2.

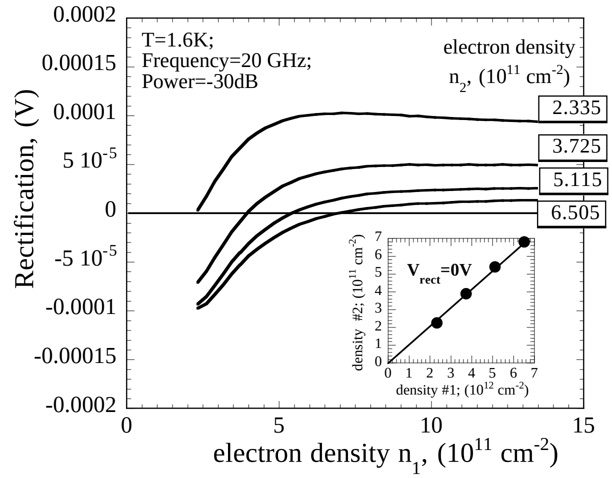


FIG. 2. Rectified signal versus electron density of 2D-metal #1, with the electron density of 2D-metal #2 kept constant at the labeled values. $T = 1.6$ K, the frequency of radiation is 20 GHz and the power attenuation is -30 dB. The insert shows the electron density of 2D-metal #2 versus electron density of 2D-metal #1 at which the rectified signal changes polarity (goes through zero).

By varying the frequency of the microwave radiation, which changes the configuration of the electromagnetic field near the sample, it was possible to vary the relative contributions of vertical and horizontal splits to the measured nonlinear signal. Measurements were taken at a frequency near 20 GHz, where the nonlinear contribution from the vertical splits was negligibly small (less than $3-5\%$). Thus, the individual nonlinear properties of each horizontal split were studied in the experiment. Fig.1 (b) shows a simplified diagram of the experimental setup near the horizontal split; the two two-dimensional metals with electron density controlled independently by gates #1 and #2 are connected through the conducting region under the split. The rectified signal, a DC voltage V_{dc}, is observed in response to a microwave electric field E_ω applied to the structure as shown in Fig.1. The voltage V_{dc} was measured with respect to ground using a high input impedance (10 GΩ) voltmeter. DC currents flowing through the system were thus exceedingly small, and the odd-order nonlinear signals $(3, 5...)$ of the different contacts provided negligible contributions to the measured rectified signal. Microwave radiation of frequency $20-40$ GHz was provided by a loop antenna maintained at the end of a microwave coaxial line. The sample was placed near the radiation loop at a distance of about 1 cm. The axis of the microwave loop was approximately parallel to the vertical splits, shifted from them by approximately 0.5 cm along the sample plane. The sample sizes are $480 \times 50\mu\text{m}^2$. A microwave YIG generator with electronically controlled frequency supplied a regulated microwave power of about 1 mW (0 dB) at the end of the coaxial line. The sample was mounted on a rotating platform at the end of a low temperature He-3 probe. Measurements were taken in an Oxford He-3 system in the temperature range $0.25-12$ K for different microwave power in magnetic fields up to 12 T applied parallel to the plane. The multigated Si MOSFET samples used in these experiments had electron mobilities of about 2.5 m^2/Vs at 0.3 K. Three different contacts were investigated; all demonstrated similar non-linear properties.

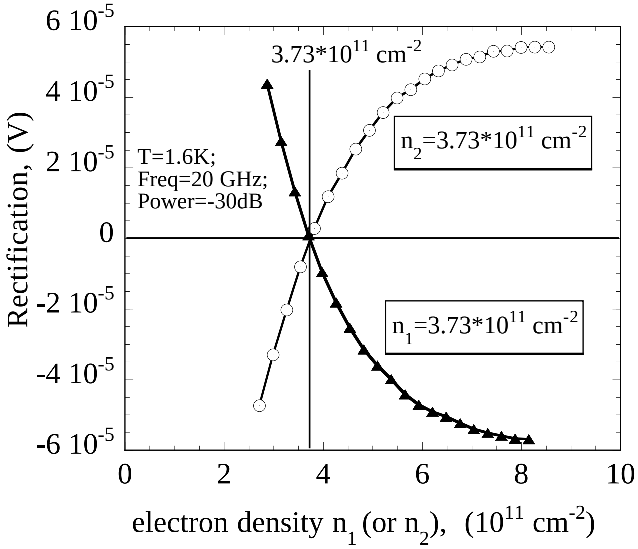


FIG. 3. Open circles denote the rectified signal plotted as a function of electron density of 2D-metal#1 while the electron density of 2D-metal#2 is kept constant at $3.73x10^{11}$ cm$^-2$. The triangles show the rectified signal plotted versus electron density of 2D-metal#2 when electron density of 2D-metal#1 is kept constant at $3.73x10^{11}$ cm^2. For both curves the rectification is zero when the densities of the two metals are equal. Note that if n_1 and n_2 are interchanged the rectification changes sign and is nearly symmetric with respect to the horizontal axis.

III. EXPERIMENTAL RESULTS

A. Density dependence

Fig. 2 shows the dependence of the rectified signal on the electron density of two adjacent 2D metals. The density of electrons in the main 2D area is fixed by the main gate at some value, as labeled, while the electron density in the contact area was varied. The rectified signal depends strongly on the electron density, changing polarity when the electron densities of the two metals are nearly the same. The insert shows the relation between the two densities n_1 and n_2 for which the signal changes sign. The correlation observed between the electron densities on different sides of the boundary demonstrates that the microwave rectification is generated by a region near to the boundary between the two 2D metals; there is almost no rectification when the two metals have the same electron density. This implies that the microwave rectification by the 2D metals [9] is much smaller than the rectification associated with the boundary between them. The symmetry shown in Fig. 3 provides additional support for this conclusion. Fig. 3 demonstrates an inversion of the density dependence of the rectification when the gates are interchanged. Curve (a) corresponds to measurements when the main gate voltage was fixed and the contact gate voltage was varied while curve (b) shows the results obtained for a fixed voltage on the contact gate when the main gate voltage was varied. The almost perfect symmetry observed when the gates are interchanged demonstrates directly that the observed rectification originates near the boundary between the two two-dimensional metals.

At fixed difference of electron densities of the two metals the magnitude of the rectified signal decreases considerably with increasing density (see fig. 2). This decrease indicates that the mismatch in physical properties responsible for the nonlinearity at the boundary between the two metals becomes relatively small at high electron densities.

B. Dependence of the rectification on microwave power

The rectified signal exhibits different behavior as a function of microwave power at low (0.25 K) and high (1.6 K) temperatures. The nonlinear response is weaker at high temperature than at low temperature.

At high temperature (T=1.6 K) the rectified voltage is proportional to the square of the microwave electric field E_ω^2 at small microwave power (<-30 dB), indicating that this is the weak (perturbative) nonlinear regime (see Fig.4 (a)). However, at higher microwave excitation (> -30 dB) strongly nonlinear behavior is observed: $V_{dc} \sim E_\omega$.

At low temperature the rectified signal is roughly proportional to the square root of the microwave power $V_{dc} \sim (P_\omega)^{1/2} \sim E_\omega$ at all available powers if one of the two metals is kept at a low electron density ($\sim 1 \times 10^{11}$ cm^{-2}), while the other is held at high electron density (see Fig. 4 (b)) [10]. Such strong nonlinearity of the conducting boundary between two metals is unusual. Estimates based on the Boltzmann equation (see below) show that a weak, perturbative nonlinear response is expected over the entire range of microwave powers used in our experiments.

The strong nonlinearity $V_{dc} \sim (P_\omega)^{1/2}$ of the boundary is similar to the strong nonlinear (high power) behavior of an ordinary diode [11]. Using the analogy with a diode, we can estimate the amplitude of the microwave voltage V_ω across the boundary. The current voltage characteristic of a diode is [11]

$$I(V) = I_0[e^{(eV/kT)} - 1] \quad (1),$$

where I_0 is the reverse current and T is the temperature. Below we will assume that the $I - V$ characteristic of the boundary between two metals is similar to that of a diode. The high power (or strongly nonlinear) regime corresponds to the condition $eV \gg kT$.

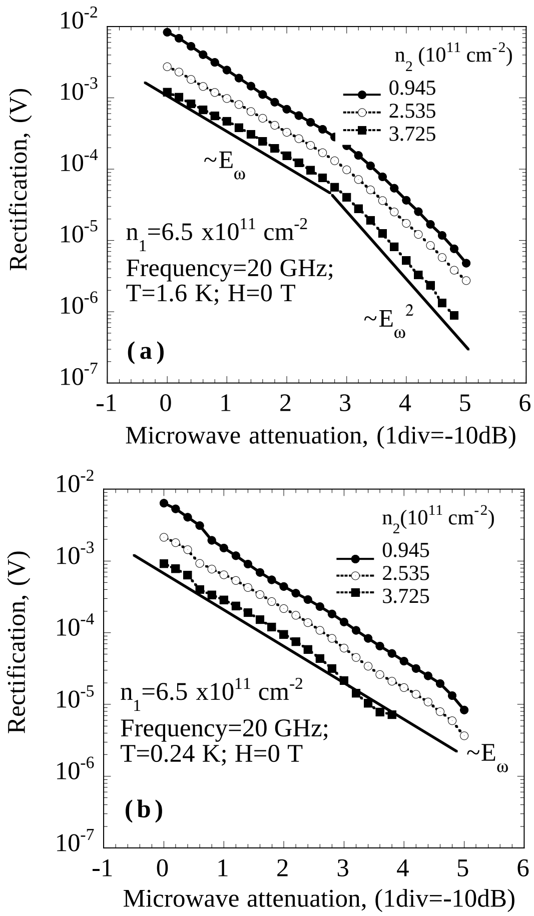


FIG. 4. a) Rectified signal versus microwave attenuation on a logarithmic scale. One division of the horizontal axis represents a -10 dB change of the microwave intensity. The curves are taken for three different values of electron density of 2D-metal #2 and fixed electron density of 2D-metal #1, as shown. The two solid curves represent linear dependence and quadratic dependence of the rectification on the amplitude of the microwave field E_ω. (a) At T=1.6K the dependence of the rectified signal on microwave amplitude changes from quadratic (perturbative regime) to linear (strong nonlinear regime). b) At T=0.24K only linear dependence on the microwave amplitude is observed (strongly nonlinear regime).

In the presence of the microwave field, the voltage drop across the boundary is $V = V_\omega + V_{dc}$, where $V_\omega = E_\omega d$ (d is the thickness of the boundary) is the voltage due to the microwave radiation and V_{dc} is the measured dc rectified voltage. In order to yield zero dc current, the dc voltage V_{dc} must be comparable with V_ω at $eV \gg kT$. This follows directly from an estimate of the average (dc) current $< I(V) >= 0$ in the strongly nonlinear regime, ($eV \gg kT$), using the diode $I - V$ curve (see Eq. (1)). This conclusion should be valid qualitatively for any other strongly nonlinear $I - V$ curves. Thus, the magnitude of the microwave voltage drop across the boundary between two metals should be of the order of the rectified signal in the high power regime: $V_\omega \approx V_{dc}$.

According to Eq. (1) the crossover to the perturbative regime ($V_{dc} \sim E_\omega^2$) should appear at $eV_\omega \approx kT$, which gives $eV_{dc} \approx kT$ at the crossover. The rectified voltage $V_{dc} \approx 10^{-4}V$ at the crossover (see Fig. 4 (a)). Therefore the crossover temperature is $T_{cross} \approx eV_{dc}/k = 1.2$ K, which is of the same order as the temperature of the experiment - $T = 1.6$ K (see Fig. 4 (a)).

C. Temperature dependence of rectification

As shown in Fig. 4, the rectified signal V_{dc} is a weak function of temperature in the strongly nonlinear regime. In the perturbative nonlinear regime ($V_{dc} \sim E_\omega^2$) the microwave rectification increases substantially with decreasing temperature T. Fig. 5 shows the temperature dependence of the rectified signal at different electron densities, as labeled.

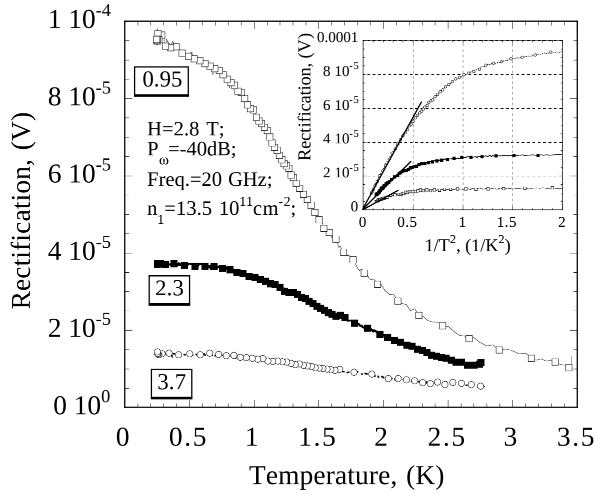
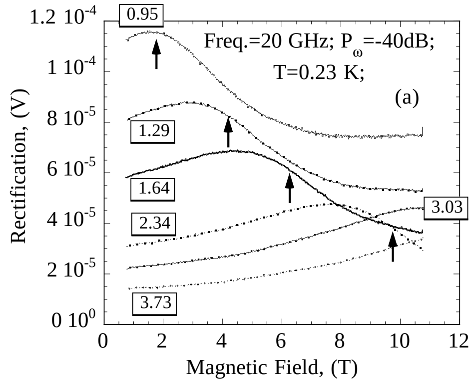


FIG. 5. Rectification versus temperature. The electron density of 2D-metal #1 is kept constant at $n_1 = 13.5x10^{11}$ cm^{-2}. The electron density of 2D-metal #2 is different for different curves as labeled in units of 10^{11} cm^{-2}. The magnetic field is 2.8 Tesla. The insert shows the same data plotted versus $1/T^2$.



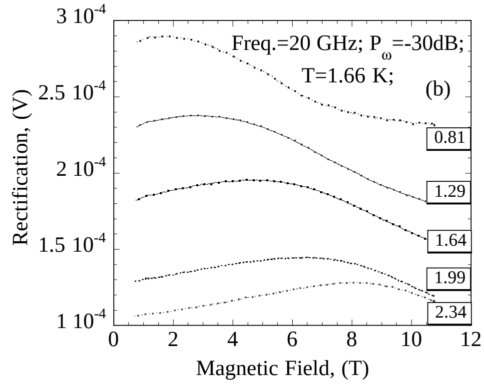


FIG. 6. (a) Rectification versus in-plane magnetic field at $T = 0.23$ K. Curves are taken for different fixed electron densities in the main area. Values of electron density in units of 10^{11} cm^{-2} are labeled. The arrows indicate the magnetic fields corresponding to complete spin polarization of the electrons under the main gate [7]. (b) Rectification versus in-plane magnetic field at $T = 1.66$ K. The direction of the magnetic field is parallel to the boundary between the two metals.

The data were obtained at finite magnetic field to avoid a change (about 20%- 30%) of the microwave field E_ω near the sample due to the superconducting transition of the Al gate at $T_c = 1.4$ K. The increase of the nonlinearity with decreasing electron temperature indicates that the conductivity itself is not the relevant parameter responsible for the rectification. The electrical charge accumulation near the boundary due to the microwave field, one of the possible mechanisms responsible for the rectification, should be less important at lower temperature due to the higher conductivity of the dilute 2D system at low T.

The saturation of the temperature dependence at low temperature may be related partially to overheating of the electrons by the microwave radiation as well as to the transition from the regime where $V_{dc} \sim E_\omega^2$ to the regime where $V_{dc} \sim E_\omega$ (see Fig. 4). The insert to Fig. 5 demonstrates the high temperature behavior of the signal. At high temperature the rectification is proportional to $1/T^2$ at different electron densities. The T^{-2} dependence of the rectification is different from the $1/T$ dependence expected for a regular diode. Using the parameter $eV/kT = (V_{dc} + V_\omega)/kT$ as a small perturbation in Eq. (1), the rectified signal was found to be: $V_{dc} \sim V_\omega(eV_\omega/kT)$.

D. In-plane magnetic field dependence of rectification

The dependence of the rectified signal on in-plane magnetic field is shown in Fig. 6 for different electron densities at two different temperatures. The contact gate area was kept at high electron density $n_1 = 13.5 \times 10^{11}$ cm^{-2}. Different curves correspond to different electron density under the main gate, as labeled. The direction of the magnetic field is parallel to the boundary between the two metals. The rectification is a nonmonotonic function of in-plane magnetic field. The arrows shown in Fig. 6 indicate the magnetic fields corresponding to complete spin polarization of the electrons under the main gate [7]. The magnetic field of about 12 T was not sufficient to fully polarize the high density of electrons under the contact gate [4].

IV. DISCUSSION

The mechanism that gives rise to the observed rectification is unknown and is the subject of current investigation. Although they are expected to be important, it is currently unclear how to include the effect of electron-electron interactions. In this section we first consider a simplified model of non-interacting electrons and show that these simple considerations do not account for our observations. We then speculate about other possible explanations.

The observed rectified signal depends on the difference between electron densities in the two 2D layers (see Fig.2). Almost perfect symmetry of the effect with respect to exchange of the gate voltages (see Fig.3) indicates that the rectification is generated near the boundary separating the two 2D electron systems. It is well known [16], that there is an internal electric field near the boundary separating two metals. This electric field creates a contact difference of potentials $\Delta\phi$. The difference in contact potentials is equal to the difference of the work functions or chemical potentials $\mu_{1,2}$ of the metals considered independently (in other words, when the metals are not connected to each other). At thermodynamic equilibrium the chemical potential has to be the same when the system is connected. Thus, the potential

difference $\Delta\phi = \mu_2 - \mu_1$ should be generated near the boundary.

Let us assume that the contact difference of potentials $\Delta\phi = \mu_2 - \mu_1$ is the main reason for the rectification near the boundary between the two metals. This suggestion is completely consistent with the symmetry of the effect with respect to exchange of the gate voltages (see Fig.3). Below we estimate the rectification of the microwave radiation near the conducting boundary between two normal 2D metals using the Boltzmann equation.

To simplify the following calculations we introduce a model where a pair of 2D metals contiguous through the conducting boundary is replaced by a single metal of strongly inhomogeneous electron density (see Fig. 1 (c)). The inhomogeneity along the direction perpendicular to the boundary between the original 2D metals is created by the voltages applied to the gates. We choose a coordinate system where the boundary lies along "y" axis. Then both the electron density and the chemical potential depend on "x" ($\mu(x) = \frac{n(x)}{D_0}$, where D_0 is the electron density of states at the Fermi surface).

The Boltzman transport equation for the electron distribution function $f(x, \mathbf{p}, t)$ is taken within the relaxation time approximation:

$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + \frac{\partial \mathbf{p}}{\partial t}\frac{\partial f}{\partial \mathbf{p}} = -\frac{f - f_{eq}}{\tau} \tag{2}$$

where the function f_{eq} describes the equilibrium state of the electron system in the absence of the microwave radiation $E(t)$ and equals the Fermi distribution function:

$$f_{eq} = f_0(\varepsilon, \mu(x), T). \tag{3}$$

Following [9] we expand $f(x, \mathbf{p}, t)$ in harmonic polynomials, keeping the first three terms of the expansion. Such an approximation is justified for a weak microwave field because the next terms of the expansion give smaller corrections in terms of the microwave field magnitude. Substituting the expansion into the Boltzman equation we get a set of equations:

$$\frac{\partial f_1^\alpha}{\partial t} + \frac{e}{m}E_\alpha(t)\frac{\partial f_{eq}}{\partial \varepsilon} + 2e\left(E_\beta(t) + \frac{1}{e}\frac{\partial \mu}{\partial x}\delta_{\beta x}\right) f_2^{\beta\alpha}$$

$$-e\frac{p^2}{2m}E_\alpha(t)\frac{\partial f_2^{\alpha\beta}}{\partial \varepsilon}\delta_{\alpha\beta} = -\frac{f_1^\alpha}{\tau}; \tag{4}$$

$$\frac{\partial f_2^{\alpha\beta}}{\partial t} + \frac{e}{m}E_\alpha(t)\frac{\partial f_1^\beta}{\partial t} = -\frac{f_2^{\alpha\beta}}{\tau}. \tag{5}$$

Here $f_1^\alpha, f_2^{\alpha\beta}$ are the coefficients of the expansion of the electron distribution function in harmonic polynomials; m is the electron effective mass, $\alpha, \beta = x, y$.

The term $\frac{1}{e}\frac{\partial \mu}{\partial x}\delta_{\beta x}$ in (4) describes the internal "electrochemical" field arising from the inhomogeneity of the electron density. In the absence of the time dependent field $E(t)$, this term balances the external field produced by the gate voltages and provides equilibrium of the electron system.

Solving Eqs. (4), (5), we can calculate the dc contribution to the electron current density. This rectified current is generated perpendicularly to the boundary (along the "x" direction). In the present experiments, where the microwave frequency ω is smaller than the effective collision frequency ($\omega\tau < 1$) we arrive at the simple expression for the rectified current:

$$j_{dc} = -\frac{4e^3\tau^3}{\pi m^2}\frac{\partial n}{\partial x}E_\omega^2, \tag{6}$$

which enables us to estimate V_{dc} as follows:

$$|V_{dc}| = \left| \int_{-\infty}^{\infty} \frac{j_{dc}(x)}{\sigma_0(x)} dx \right|. \tag{7}$$

Here $\sigma_0(x)$ is the Drude conductivity corresponding to electron density $n(x)$ and relaxation time $\tau(x)$.

It was observed in the present experiments that when the minimum $n(x)$ is larger than a certain value n_0 ($n_0 \approx 2.5 \times 10^{11}$ cm^{-2}) the relaxation time τ is nearly independent on the electron concentration and can be treated as a constant in carrying out the integration over "x"in (7). Using this approximation we get:

$$|V_{dc}| = \frac{4}{\pi}\frac{e}{m}\tau^2 \ln\frac{n_1}{n_2}E_\omega^2. \tag{8}$$

These results based on the Boltzman transport equation are in agreement with the experiments in several important respects. First, it follows from (6)–(8) that rectification can take place only when there exists a difference in the electron densities of the 2D metallic regions separated by a conducting boundary. Secondly, the above considerations give a correct relation between V_{dc} and E_ω for small power levels of the microwave field ($V_{dc} \sim E_\omega^2$).

There are, however some discrepancies between the theoretical model and the experiments. Using the thickness of the boundary $d \approx 0.1\mu$, the electric field near the boundary is estimated to be $E_\omega \approx V_{dc}/d = 10^3 \frac{V}{m}$ at microwave attenuation -30dB and the temperature $T = 1.6K$ (see fig. 4(a)). Using the estimates $m \approx 0.2m_0$ (m_0 is the mass of a free electron), $\tau \approx 3 \times 10^{-12}s^{-1}$ and eq.(8), we obtain $V_{dc}^{est} \sim 10\mu V$, which is less than the rectification $V_{dc} \approx 100\mu$ observed at -30dB at $T = 1.6KT$ experimentally (see fig.4(a)). Moreover the perturbative parameter used in the Boltzman approach is proportional to the ratio of microwave electric potential $V_\omega \approx V_{dc} \approx 10^{-5}$ V at -40 dB (see Fig.4b) to the contact difference of potentials $\Delta\phi = \mu_2 - \mu_1 \approx 4$ mV formed at the boundary between two metals. This ratio is about 10^{-2} in our experiment at P_ω=-40 dB, which according to the above approach indicates we're in the perturbative regime of rectification: $V_{dc} \sim E_\omega^2$ (see eq.(8)).

However this contradicts our experimental observations at these microwave power levels (see Fig.4b): $V_{dc} \sim E_\omega$ at $n \approx 1 \times 10^{11}\ cm^{-2}$.

The magnetic field dependence of the rectification exhibits nonmonotonic behavior. This behavior can be qualitatively understood in terms of the competition between two effects. The dependence of the chemical potential of the electrons with magnetic field is given by $\Delta\mu = -1/2(d\chi/dn) \times H^2$, where we have assumed that $(d\chi/dn)$ is independent of magnetic field. The derivative of the magnetic susceptibility with respect to electron density, $(d\chi/dn)$, is negative due to the decrease of the magnetic susceptibility $\chi(n)$ with increasing electron density [5,6]. The increase of the chemical potential appears to be stronger at low electron density in Si-MOSFET's. This implies that the difference of the chemical potentials $\mu_2 - \mu_1$ is reduced in a magnetic field, decreasing the rectification. On the other hand, the conductivity σ is also reduced, with a consequent increase in the rectification (see eq.(7)). Careful analysis of these competing effects is needed in order to understand the dependence of the rectification on magnetic field.

The strong nonlinearity observed in these experiments appears to be similar to the response of an ordinary diode. It is well known that the diode rectification is proportional to the amplitude of the electric field in the high power regime. In the case of an ordinary diode, the rectification is due to the potential barrier formed between the p and n regions, which induces an exponential dependence of the current on applied voltage [11]. Another important property of the diode is the presence of two kinds of carriers: electron and holes. Below we will consider these possibilities.

One of the reasons for the potential barrier is simple electrostatics. The barrier could be the result of the finite width d of the split between two gates. When the voltages of the gates are equal, then a drop in density will occur under the split. However the width of the split, $d = 50 - 70$ nm, is smaller than the distance between the 2D electrons and the gates $d_{ox} = 150$ nm. Therefore, the decrease in density is expected to be quite small. Moreover at large differences between the gate voltages (an order of magnitude in our experiment) there is a very sharp drop in the electron density. In this case one expects a monotonic change in electron density between the two metals [8]. We must also note that even in the presence of such an electrostatic potential barrier the rectification should be absent at low microwave voltages [17].

An additional potential barrier between two dilute metals could also arise due to the presence of different charged excitations in a 2D dilute system on a Si surface, as proposed in several papers [12–15]. For example, if the majority carriers in one metal are Fermi particles while the other 2D metal contains mostly Bose particles (for example paired electrons) with an energy of dissociation Δ, then an additional potential barrier can, in principle, be formed between the two metals. The origin of such an electrochemical barrier is the reaction of formation of the Bose particles $e + e = 2e$ (or other correlated structure). A similar electrochemical barrier will be formed also between two metals with different strength of the electron-electron interaction. The $1/T^2$ temperature tail of the rectification (see fig. 5) indicates that the energy scale responsible for the rectification effect is proportional to the T^2. This energy scale has the same temperature dependence as the rate of electron-electron scattering in a metal.

Finally, the observed rectification could be the result of variation of the density of electron states with energy. However, the very strong nonlinear response observed in our experiments would require that the density of electron states be a very strong function of energy.

V. CONCLUSION

In summary, we report the observation of the rectification of microwave radiation by the boundary between two two-dimensional metals on the surface of Si. The effect was investigated as a function of electron density, microwave power, temperature, and in-plane magnetic field. The rectified voltage depends on the densities of the two metals, and goes to zero when the electron densities are equal. At the lowest measured temperature $T = 0.23$ K the rectified signal is directly proportional to the amplitude of the microwave field if one of the metals is close to the quantum phase transition [7], while the other is kept at high electron density. This signals a strongly nonlinear regime even when the contact potential difference between the metals is much larger than the potential associated with the microwave field.

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[1] E. Abrahams, S. V. Kravchenko, and M. P. Sarachik, Rev. Mod. Phys.**73**, 251 (2001).

[2] T. Okamoto, K. Hosoya, S. Kawaji, and A. Yagi, Phys. Rev.Lett. **82**, 3875 (1999).

[3] S. A. Vitkalov, H. Zheng, K. M. Mertes, M. P. Sarachik and T. M. Klapwijk, Phys. Rev. Lett. **85**, 2164 (2000).

[4] S. A. Vitkalov, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. **B 64**, 073101, (2001).

[5] A. A. Shashkin, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. Lett. **87**, 086801, (2001).

[6] V.M.Pudalov, M. Gershenson, H.Kojima, preprint cond-mat/0110160

[7] S. A. Vitkalov, H. Zheng, K. M. Mertes, M. P. Sarachik and T. M. Klapwijk, Phys. Rev. Lett. **87**, 086401, (2001).
[8] R. Heemskerk, Ph. D. Thesis, University of Groningen, (1998).
[9] V. I. Falko Sov. Phys. Solid State **31**, 561 (1989)
[10] The small ($< 10\mu V$ rectification signal (not shown in the fig.4a) at high density is comparable with an offset voltage at $T = 0.24K$. It needs an additional study.
[11] S. N. Levine "Principles of Solid-State Microelectronics", New York, 1963.
[12] D. Belitz and T. R. Kirkpatrick, Phys. Rev. B **46**, 8393, (1992); *ibid.* **58**, 8214 (1998).
[13] P. Phillips, Y. Wan, I. Martin, S. Knysh, and D. Dalidovich, Nature (London) **395**, 253 (1998).
[14] S. Chakravarty, S. Kivelson, C. Nayak, and K. Voelker, Philos. Mag. B **79**, 859 (1999).
[15] Claudio Chamon, Eduardo R. Mucciolo, Antonio H. Castro Neto preprint cond-mat/0107271, (2001).
[16] L. D. Landau and E. M. Lifshitz "Electrodynamics of Continuous Media", Pergamon Press, (1984).
[17] J. G. Simmons Journal of Appl. Phys. **34**, 2581 (1963).